
Development of LArTPC Vertical Drift Solutions with PCB Anode Readouts for DUNE

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Liquid Argon Time Projection Chamber (LArTPC) with its superior capability in particle tracking and energy calorimetry may hold the key to answer some critical questions about our Universe including i) why is matter dominating antimatter? ii) can the proton decay? iii) how do core-collapse supernovae happen? iv) are there additional neutrino flavors? LArTPC is the chosen detector technology for the Long Baseline Neutrino Facility (LBNF)/Deep Underground Neutrino Experiment (DUNE) [1], which is a top priority of U. S. High Energy Physics (HEP). LBNF will provide excavated underground space for four 10-kton LArTPCs. The success of the first-generation LArTPC experiments: ICARUS [2], MicroBooNE [3], and ProtoDUNE NP04 [4, 5], has led to the decision that the first 10-kt DUNE detector module is going to be a single-phase LArTPC [6] utilizing multiple wire-plane readout with cold electronics [7] inside LAr. Currently, the DUNE-US project scope includes only the first detector module. The design of the remaining three 10-kt detector modules is open to support international partners, and a detector upgrade program is essential to LArTPCs with improved performance and cost-effective robust construction/operation. We thus propose to develop the next-generation LArTPC detector technology with improved physics capability and more robust performance, aiming to be implemented in the future 10-kt detector modules in DUNE. R&D on the next-generation LArTPC technology is critical to ensure international investment and funding of the overall project.

I. A VERTICAL DRIFT SOLUTION

The first generation of LArTPCs use multiple layers of wires with different orientations. The construction of these anode plane assemblies is a time consuming, costly, and labor-intensive endeavor. Leveraging the recent development and existing European investment in the Printed Circuit Board (PCB) anode plane structure in the dual-phase (DP) ProtoDUNE (NP02) detector [8], a new concept was introduced at CERN in which a modified large electron multiplier (LEM) PCB is submerged in the LAr to sense ionization signals without any electron amplification [9]. This anode PCB construction avoids several challenges in the DP LArTPC design, while allowing for a vertical ionization electron drift. The latter can take advantage of existing development in constructing and installing field cage and advancement in the high voltage.

The concept of the vertical drift is presented in Fig. 1a. Two separate drifts volumes of 6.5 m each in DUNE, divided by a cathode plane in the middle. Two anode readout planes, one on the top, serving the upper vertical drift volume, one in the bottom serving the lower drift volume. The modularity is of $3 \times 3 \text{ m}^2$ of a detector module (Fig. 1b). The necessary homogeneous electrical vertical field is provided by a large field cage, placed as near as possible to the cryostat vertical walls to maintain an electric field of 500 V/cm. Photon detectors (PD) will be instrumented on the cathode planes, following the technologies developed for the NP04 ProtoDUNE demonstrator. The SiPMs in the PDs on the cathode are powered using power over fiber (PoF), and the output signals are also transmitted through optical fibers.

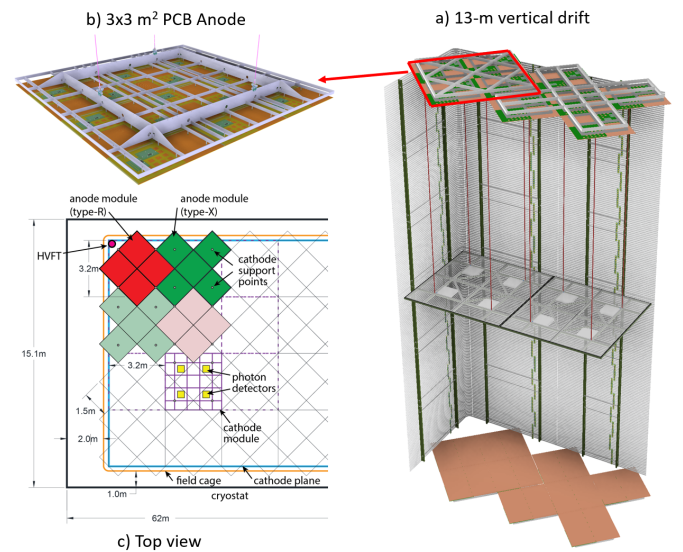


FIG. 1. Next-generation LArTPC concept: a Vertical Drift Solution with the PCB Anode Readout.

A. PCB Anode Plane with Cold Electronics

The new design of PCB anode plane TPC readout has several advantages with respect to the wire readout. One such example is the inefficient induction plane signal processing for the prolonged TPC signals that have long extension in the drift time [10, 11]. With LEM PCB, the ionization electrons are forced to go through the small hole. The closest distance between the ionization electrons and the induction electrode can be much smaller than that of the wire readout leading to a larger induced signal in the induction plane. The increased signal size, paired with reduced electronics noise with cold electronics [12] and the advanced signal processing procedure incorporating deep learning techniques [13], is expected to significantly reduce the inefficiency of the induction-plane readout. The most recent test of the anode PCB, adapted a set of cold electronics developed for ProtoDUNE [14] demonstrated excellent signal

to noise ratio in a small LArTPC at CERN. Another example is the ambiguities when particles are traveling close to parallel to the anode plane, which is directly visualized with 3D event reconstruction [15]. Such ambiguities are reduced in the vertical drift solution because of a finite angle between the anode plane and the neutrino beam direction.

Figure 1c illustrates a possible layout of a TPC using horizontal PCB anode modules. Each module is a $1.5\text{ m} \times 1.5\text{ m}$ basic anode panel with two sets of orthogonal strips 1.5 m long. To optimize the readout strip angle with respect to the beam, the PCBs are rotated 45 degrees. There are two types of anode module configurations: a 4 panel rhombus shape and a 5 panel X shape. These two types of modules are interleaved to tile the entire top and bottom of the detector, forming a 4 row, 18 column array. If a 5 mm strip pitch is used, there will be a total of 388,800 readout channels in the entire detector, similar to that of the first detector module with wire readout. A 3-view readout configurations can be achieved by splitting the collection view into two as the design in NP02. Jumpers may be used to connect some channels from adjacent PCB modules together to reduce the overall number of channels. To enhance the light collection efficiency for the near anode events, the induction strips that are on the front side of the PCB can be coated with an insulating layer with wavelength-shifting (WLS) material.

B. Photon Detector with PoF transmission

Photon detectors (PD) in LArTPCs are generally used for t_0 determination and triggering purposes. In case an efficient photon detector with sufficient coverage, the use of scintillation light can be extended to calorimetric energy reconstruction, as recently demonstrated in ProtoDUNE-SP. This opens the way to improvement of detection efficiency and energy resolution by combination of both the charge and the light signals, particularly important for detection and reconstruction of low energy underground events. In the first DUNE 10-kt module, thin bar-shaped PD modules (ARAPUCA technology) are integrated in the APA frames, occupying the space between the two ground mesh planes. Silicon photo-sensors (SiPM) are used to convert the light to electrical signals, which are brought out of the cryostat on copper cables. In the Vertical Drift LArTPC layout, the PCB plane structure is largely opaque and does not permit for PD installation at the anode side of the TPC. Photon detector modules will thus be integrated in the cathode plane, ie promoting the cathode plane into a photo-sensitive cathode plane, with the photo-sensors operated on HV surfaces (-325 kV). To overcome this non trivial constraint, the SiPMs are powered on the cathode using power-over-fiber (PoF) technology, and the output signals are also transmitted off the cathode through optical fibers. The basic layout of a PoF based PD system consists of three cold units onto the cathode (or embedded in the cathode plane) inside the cryostat, and two external units.

C. High Voltage System

To reach the -325 kV bias voltage, some further improvements on the HV feedthroughs (HVFT) used by NP04 and NP02 (tested at 300 kV) are needed. A 6.5 m long HV extender is required to be installed between the HVFT and the cathode. Several design concepts exist to improve what has been implemented in NP02. A HVFT penetration at the mid height of the cryostat is also being considered. NP02 has demonstrated the simplicity of constructing, and installing a field cage in a vertical drift TPC. An improved version of this field cage design, which has been developed for the DUNE DP far detector module, can be directly applied. The cathode plane, consisting of $3.2\text{ m} \times 3.2\text{ m} \times 5\text{ cm}$ modules, will be a complete new design. The 3.2 m dimension matches the 1.6 m cryostat warm structure pitch simplifying the detector support penetration layout. The cathode is constructed from a fiber reinforced plastic (FRP) frame covered with stainless steel wire mesh on the two sides. Photon detector modules are mounted to the FRP frame inside a few selected pockets and enclosed by the stainless steel mesh to prevent charging up in the TPC in addition to the physical protection. This cathode module is supported through 4 FRP round tubes to the upper anode plane. The power and output fibers for the PDs can be embedded in these support hangers to reach the top of the cryostat. Additional light containment can be achieved by installing reflector foils with WLS coating in the empty cells in the cathode frame and the field cage.

II. SUMMARY

While LBNF will provide excavated underground space for four 10-kton LArTPCs, the current DUNE-US project scope includes only the first detector module. R&D on the next-generation LArTPC technology is critical to support international partners. Leveraging the existing development in Europe, the development of the vertical drift solution with the PCB anode readout concept is critical to ensure international investment and the overall funding of DUNE.

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